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**SPECTRALLY NARROW MID-INFRARED  
OPTICALLY PUMPED LASERS WITH PARTIAL  
SURFACE DBR (POSTPRINT)**

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# Spectrally narrow mid-infrared optically pumped lasers with partial surface DBR

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**Abstract:** An optically pumped mid-infrared edge-emitting laser is described, in which a Distributed Bragg Reflector grating partially occupies the surface, and provides spectral narrowing in a high power device. A quasi-continuous-wave power of 3 Watts is obtained at 3.6  $\mu$ m that is contained within a spectral width of 7 nm.

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## 1. Introduction

The 3–4  $\mu$ m wavelength range is important for spectroscopic measurement of gases because it contains many fundamental molecular absorption lines. In laser-based differential absorption spectroscopy, a smaller spectral linewidth of laser emission improves the selectivity of the absorption feature that is targeted, while higher laser power leads to increased sensitivity and/or increased range of detection. In an ideal system, therefore, the laser source will have both a narrow linewidth and high power. Such a 3–4  $\mu$ m semiconductor laser source has proven to be a challenge, and if available, would be very useful for a number of applications including the standoff detection of gaseous chemicals [1–5].

Gain-guided edge-emitting optically pumped semiconductor lasers (OPSL) that are based on type-II InAs/InGaSb/InAs quantum-wells produce multi-Watt power levels at mid-infrared wavelengths when they are operated at 80-140 K [6]. These devices are usually designed as a Fabry-Pérot (FP) cavity, and produce multi-longitudinal mode emission with a spectral width of 40-60 nm, too broad for chemical identification [1]. Unless otherwise specified, the spectral width mentioned in this paper is full width measured at  $1/e^2$  of maximum (FW1/e2M). Providing spectral selectivity while preserving high power in these devices may be very useful for spectroscopic applications.

Recently, mode selectivity in edge-emitting diode lasers was demonstrated using an etched 1st-order surface grating placed near the back facet of the device [7-8]. Such a partial surface grating acts as a Distributed Bragg Reflector (DBR) providing a narrow band of high reflectivity at one facet. The longitudinal modes that are within this DBR stopband are selectively enhanced for emission from the opposing facet.

In this study, we describe optically pumped mid-IR lasers emitting near 3.6  $\mu\text{m}$  that employ a partial surface grating (DBR-OPSL) with the goal of achieving high power and narrow spectral linewidth.

## 2. Design and fabrication

There are several considerations when designing the DBR-OPSL [9-11]. The first consideration is to minimize the mirror losses for the DBR-enhanced modes by providing high DBR reflectivity. With maximum reflectivity of the stopband  $R_{max}$  approximated as  $\tanh(\kappa L_{DBR})$ , where  $\kappa$  is the coupling coefficient, and  $L_{DBR}$  is the grating length, high reflectivity will therefore require a large  $\kappa L_{DBR}$ . However, since  $L_{DBR}$  is likely to add internal loss to the DBR-enhanced modes and should be minimized, a large  $\kappa$  will be desirable. A second consideration is to limit the number of enhanced modes by making the stopband spectrally narrow. In this case, since  $\kappa$  primarily determines the width of stopband,  $\Delta\lambda_s$ , a small  $\kappa$  is desirable. These two considerations make competing demands on  $\kappa L_{DBR}$ . Consequently tradeoffs must be made in the design. Finally, the reflection band must be aligned with the gain peak. The gain peak will shift with the temperature of the active region; therefore the grating pitch must be designed to provide the best alignment at the desired operating conditions. Since the gain peak is much broader than the DBR reflectivity band, we are particularly interested in understanding whether the DBR-enhanced modes can operate exclusively, or compete with modes outside of the DBR's reflectivity band.

Three laser structures were designed and characterized to shed light on these tradeoffs in this study. The laser structures were grown by molecular beam epitaxy on GaSb substrates. The baseline heterostructure consists of the following: a 1- $\mu\text{m}$ -thick nominally lattice-matched low-index AlAs<sub>1-y</sub>Sb<sub>y</sub> cladding layer that stops the transverse mode from extending into the high-index GaSb substrate, a 0.5- $\mu\text{m}$ -thick GaSb bottom waveguiding layer, a 1.5- $\mu\text{m}$ -thick lattice-matched In<sub>0.25</sub>Ga<sub>0.75</sub>As<sub>x</sub>Sb<sub>y</sub> waveguide core that is designed to absorb the pump radiation, and a 0.5- $\mu\text{m}$ -thick GaSb top waveguiding layer. Fourteen InAs/In<sub>0.4</sub>Ga<sub>0.6</sub>Sb/InAs type-II quantum wells that are placed within the quaternary waveguide core provide gain near 3.6  $\mu\text{m}$ .

A 1st-order partial grating was fabricated in the top clad layer using a combination of optical lithography, interferometric lithography, and inductive coupled plasma etching. A portion of the sample was masked to provide an un-etched section of the device. After lapping the wafer to a thickness of 150  $\mu\text{m}$ , individual devices with a total cavity length of 4 mm long were cleaved. Devices in the epi-up configuration were mounted on a copper heat sink, and cooled in a liquid nitrogen containing Dewar to 78 K. The lasers were optically pumped by a 1.95  $\mu\text{m}$  diode laser array, with a 250- $\mu\text{m}$ -wide pump stripe to illuminate a gain-guided cavity. A schematic of the DBR-OPSL is shown in Fig. 1. Laser output was characterized using 32  $\mu\text{s}$  pulses at 1% duty cycle. Spectral measurements were made using a monochromator with a cooled InSb detector. Output power measurements were performed by

collecting the emission from the front facet using a gold-coated ellipsoidal mirror and focusing it onto a thermopile detector.

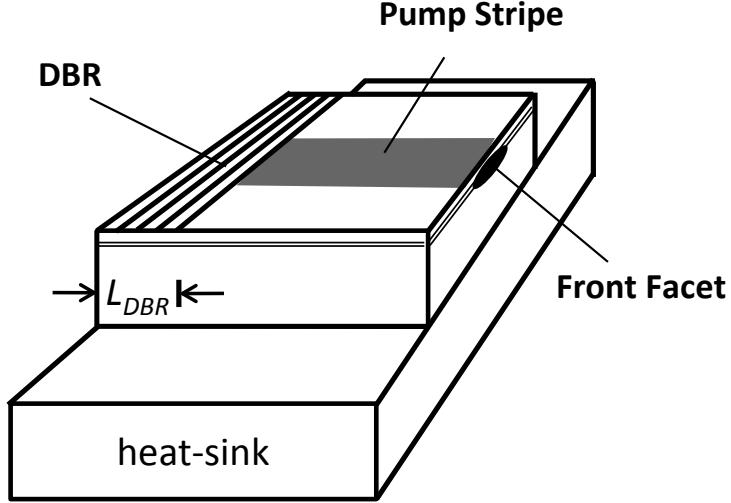


Fig. 1. Schematic of DBR-OPSL pump geometry.

### 3. Results

Device-A was designed to have a very large  $\kappa$ , (estimated to be  $200 \text{ cm}^{-1}$ ) to achieve high reflectivity, a spectrally broad stopband (estimated to be  $38 \text{ nm}$ ) to ensure alignment with gain, and a small  $L_{DBR}$  ( $0.01 \text{ cm}$ ) to minimize loss. The etched grating was  $\sim 800 \text{ nm}$  deep and  $\kappa L_{DBR}$  was estimated to be 2. Spectra collected from the front facet, the back facet, as well as a separate device processed without the DBR grating are shown in Fig. 2 for comparison.

Without a DBR grating, the FP-cavity emission is contained within a  $57 \text{ nm}$  band, with a peak near  $3470 \text{ nm}$ . Emission from the front facet of the DBR-OPSL (Device-A) is also centered at  $3470 \text{ nm}$ , and is contained within a spectral range of approximately  $22 \text{ nm}$ . The narrower spectral width is consistent with the stopband estimated for the DBR. In contrast, the emission spectrum collected from the back facet of Device-A shows lasing modes that are predominantly at either shorter or longer wavelengths than the front facet emission. At the maximum quasi-continuous-wave input power of  $41 \text{ W}$  (25 times threshold), an output power of  $3.5 \text{ W}$  was measured from the front facet. Under similar conditions, the output power from the back facet was  $1.6 \text{ W}$ , approximately  $31\%$  of the total power output. The complementary nature of the emission spectra suggests that front facet emission is comprised primarily of DBR-enhanced modes, whereas the back facet emission contains modes that are outside of the DBR stopband that can transmit through the grating to reach the back facet. It is still not clear why those non-DBR modes do not travel back to front facet.

Device-A is useful in demonstrating that the DBR-OPSL design can operate as anticipated, with DBR-enhanced modes carrying a larger portion of the power in the forward direction. Based on this information, a second device was designed with the goal of achieving narrow emission linewidth.

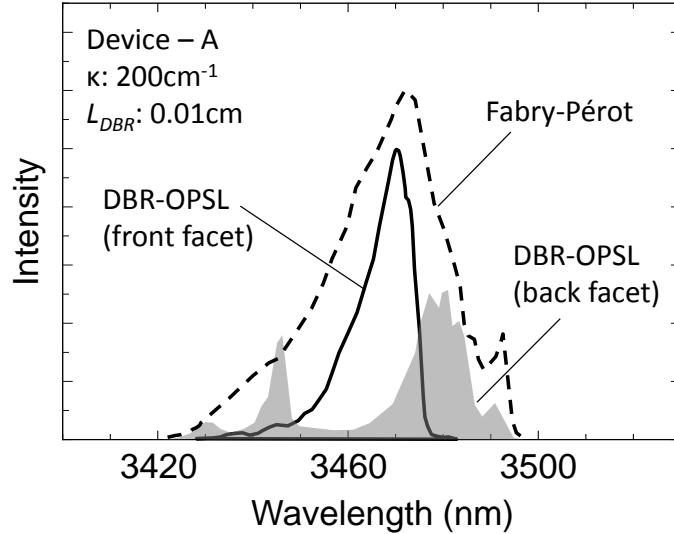


Fig. 2. Emission from Device-A collected from front facet (solid line), and back facet (gray). Also shown is emission from a device without the DBR (dashed line).

In Device-B the top clad layer thickness was increased to 1  $\mu\text{m}$ , while the rest of the heterostructure remained nominally the same. The DBR grating depth was reduced to 440 nm for an estimated  $\kappa$  of  $47 \text{ cm}^{-1}$ , and the  $L_{DBR}$  was increased to 0.05 cm to give an estimated  $\kappa L_{DBR}$  of 2.3. The DBR stopband is estimated to be 8 nm in width. The center wavelength was designed to be at 3640 nm, near the center of the wavelength chirp observed in a FP-cavity device when tested in the temperature range of 80 K to 130 K. The purpose is to deliberately shift the gain peak with temperature in order to observe the effect of the misalignment of the DBR stop-band with the gain.

Spectra collected from at various temperatures from both facets of Device-B at 15 times threshold power are shown in Fig. 3. At 88 K, the lowest temperature shown, front facet emission is characterized by two features: a narrow peak of DBR-enhanced modes near 3640 nm, and a broad band at shorter wavelengths corresponding to a collection of FP modes. The presence of FP modes can be understood by comparing this spectrum to that obtained from the back facet at the same temperature. Here, the spectrum is primarily characterized by broad band of FP modes that are shorter in wavelength than the DBR stopband. We conclude that, when the DBR is sufficiently misaligned with the gain peak, as is the case at 88 K, there will be FP modes that bypass the DBR and emit from the front surface. Interestingly, there is no emission observed at shorter wavelengths that are immediately adjacent to the DBR-enhanced peak.

At intermediate temperatures between 96 K and 120 K, front facet emission is characterized by a single peak. This peak has a width of 5.5 nm, in agreement with the stopband designed for this DBR-OPSL. This peak is observed to have a slow redshift with temperature at a rate of  $\sim 0.25 \text{ nm/K}$ . In contrast, the FP modes emitting from the back facet maintain a broad spectral envelope, and have a larger redshift rate of  $\sim 2 \text{ nm/K}$ . In this temperature range, the gain peak, as approximated by the back facet emission of FP modes, starts at shorter wavelengths, then surpasses the DBR stopband. However, all FP mode emission from the front facet appears to be suppressed in this range. We can gauge the relative misalignment of the DBR with the gain peak by comparing the wavelength of the DBR-enhanced modes with the wavelength of the FP modes that are the farthest in any direction. These differences are shown Fig. 3. FP modes that are up to  $\sim 27 \text{ nm}$  shorter, and up to  $\sim 45 \text{ nm}$  longer than the DBR stopband are effectively denied front facet emission when the DBR grating is present. One possible explanation for this behavior is that FP modes that are

near but outside the DBR stopband are subjected to higher internal losses, and cannot compete with the DBR-enhanced modes. At 128 K, the highest temperature measured, the misalignment is large,  $\sim 58$  nm. Here, the front facet emission, as in the 88 K case, is characterized by a narrow peak of DBR-enhanced modes as well as FP modes that bypass the DBR mirror.

Device-B allows us to conclude that the front-facet emission band-width will mimic the DBR stopband. It also suggests that some tolerance for misaligning the stopband with the gain peak, particularly if the stopband is slightly shorter in wavelength. Based on this information, a third device was prepared from the same epitaxial structure to optimize for a high power at the desired operating temperature of 78 K. It is evident from the data shown in Fig. 3 that at 78 K the gain peak will be near 3600 nm.

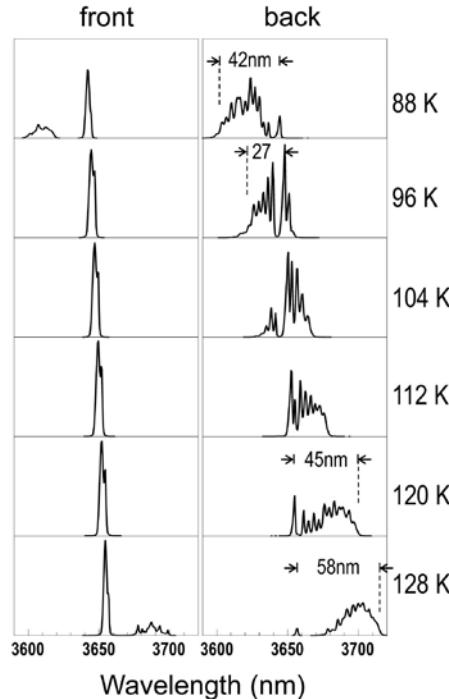


Fig. 3. Emission spectra from front facet and back facet of Device-B collected at various temperatures.

Device-C was prepared with a grating structure designed to have a stopband centered at 3595 nm. With a  $\kappa$  of  $47 \text{ cm}^{-1}$  and  $L_{DBR}$  of 0.05 cm,  $\kappa L_{DBR}$  was estimated to be 2.3, the same as Device-B. The main difference between Device-C and Device-B is that the grating pitch in Device-C is adjusted to shorten the center wavelength of the DBR stopband to within an acceptable deviation from the gain peak at 78 K, the desired operational temperature.

Output power and emission spectra collected at 78 K from the front facet of Device-C are shown in Fig. 4. The front facet emission is characterized by a single peak containing the DBR-enhanced modes. This peak is centered at 3593 nm, approximately 40 nm shorter than that in Device-B, as intended. The back facet emission spectrum collected at the highest power shows FP modes at both shorter and longer wavelengths than the front facet emission, indicating a good match between the DBR stopband and the gain peak.

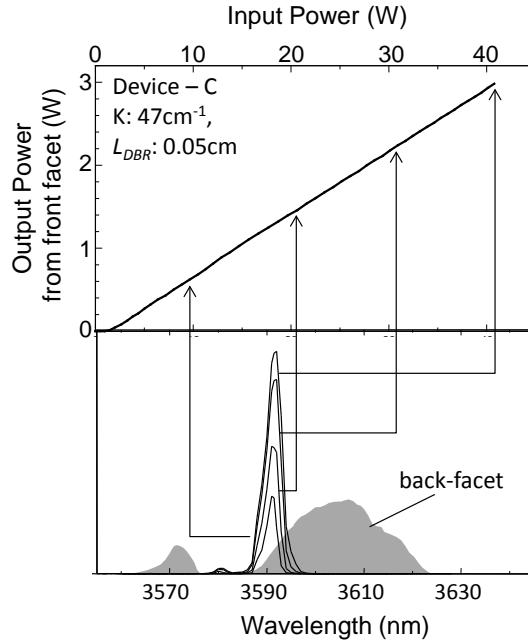


Fig. 4. Output power, and emission spectra collected from the front facet of Device-C. Back facet emission at max power is also shown in gray.

At a pump power of 41 W, approximately 25 times threshold, an output power of 3 W is obtained from the front facet. The power is similar to that obtained in Device-A. In contrast to device-A, however, more than 95% of this power is contained within a spectral range of 7 nm. Thus the DBR-OPSL embodied in Device-C demonstrates high power with a spectrally narrow emission.

Given the 3.5 mm cavity length of Device-C, the longitudinal mode spacing is approximately 0.5 nm. Consequently, the emission contains perhaps fifteen longitudinal modes that cannot be resolved in our measurements. There are two ways to reduce the number of longitudinal modes that are DBR-enhanced. One of these is to use a shorter cavity length to increase mode separation, but this is likely to reduce the power output. Alternatively, a DBR with a smaller stopband width can be designed. The results presented here can provide a guide for the further optimization of the design parameters. Since the OPSL devices used here can be designed to emit within wide range of wavelengths (2.5-9  $\mu$ m), the DBR-OPSL presents a viable means of providing high power and narrow linewidth at other spectroscopically important wavelengths, such as those useful for sensing hydrocarbons.

#### 4. Summary

In summary, we have demonstrated the concept of using a partial surface DBR grating in an optically pumped GaSb-based mid-infrared edge emitting laser to achieve spectral narrowing of the front facet emission. A high-power device delivering 3 W within a spectral range of 7 nm near 3.6  $\mu$ m is demonstrated.

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